

THE OHIO STATE
UNIVERSITY

Design of Leading Edge Vortex Flaps for Delta Wings at Low Speeds

Benjamin Wagner, Aerospace Engineering
Advisor: Clifford Whitfield, PhD, Department of Mechanical and Aerospace Engineering
The Ohio State University

Introduction

Background

Small unmanned aerial vehicles (UAVs) have become increasingly important in applications ranging from agriculture to the military. Frontline troops rely on the ability to easily deploy UAVs from any position in order to collect time sensitive intelligence. One of the primary criteria for small UAVs is that of portability. In order to address this need, it has been proposed to design a UAV with a foldable delta wing made of a flexible material. A folding delta wing design would give UAVs greater mission adaptability and allow for alternative methods of transportation.

Problem

Delta wings typically suffer from reduced aerodynamic efficiency which is the ratio of the lift created to the drag produced. Since range is directly proportional to the maximum achievable aerodynamic efficiency, a delta wing equipped UAV would need to expend more propulsive energy to accomplish a given mission in comparison to conventional designs.

Solution

A potential solution exists in the form of Leading Edge Vortex Flaps (LEVF). Essentially a flap-like control surface attached to the wings forward edge, such devices have been shown to improve aerodynamic efficiency by as much as 20 percent on conventional delta wing aircraft.

Goal

Adapt the LEVF concept to low speed, flexible delta wings by determining an optimal flap design with the goal of improving aerodynamic efficiency.

1. Determine optimal LEVF geometry
2. Improve aerodynamic efficiency
3. Determine suitability of LEVF devices as a means of control

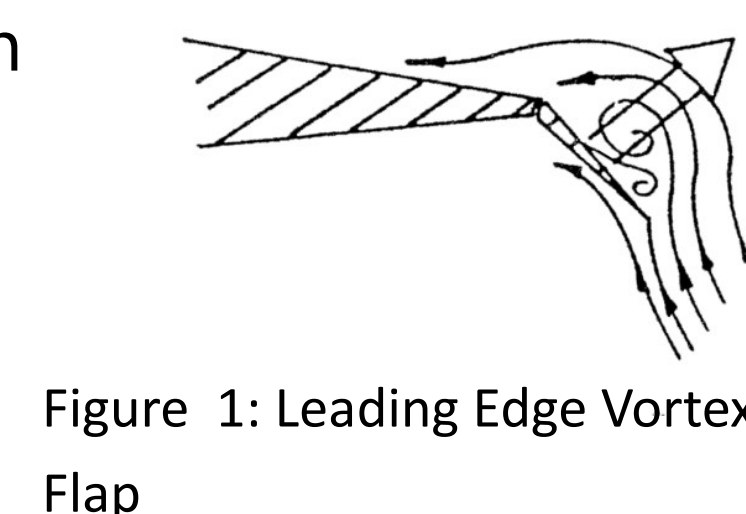


Figure 1: Leading Edge Vortex Flap

Methodology

Computational Fluid Dynamics

The primary method of investigation was computational fluid dynamics (CFD). CFD is a method of numerically approximating the physical behavior of fluids based on three fundamental conservation laws: conservation of mass, momentum, and energy. These conservation laws, commonly referred to as the Navier-Stokes equations, are typically cast as integral equations and solved over a discretized domain of finite volumes.

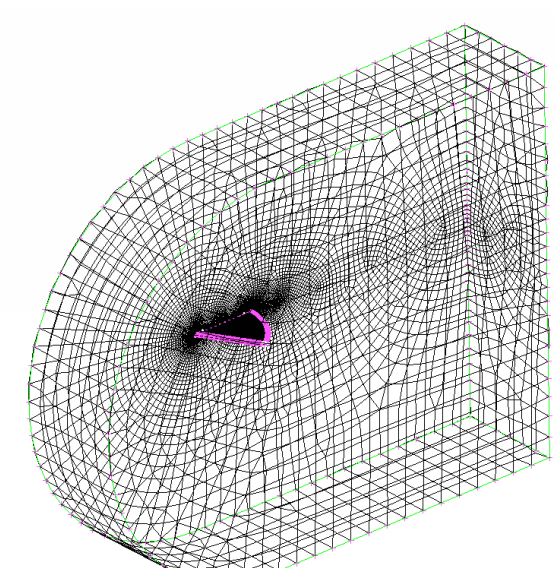


Figure 2: CFD C-Mesh

Setup (ANSYS Fluent)

- Fluid model: sea level conditions, Reynolds number = 3×10^5 , freestream velocity = 10.78 m/s
- Turbulence model: k-Epsilon with enhanced wall treatment
- Scheme: implicit, second order upwind
- Domain: unstructured C-mesh with approximately 2.4×10^6 cells



Figure 3: Half Wing Model (inches)

Flap Design Process

2 Dimensional Analysis

Vortex Flap design began by first conducting a study of two-dimensional cross sections. A flap deflection of 30 degrees was used for all test cases. Design variables included flap length, curvature, and gap.

Design Variables

- Length: 4, 8, 12 — percent of wing reference chord
- Curvature: 21, 29, 35, 40, 90 — constant radius of curvature (mm)
- Gap: 5, 10, 15 — distance from reference wing leading edge (mm)

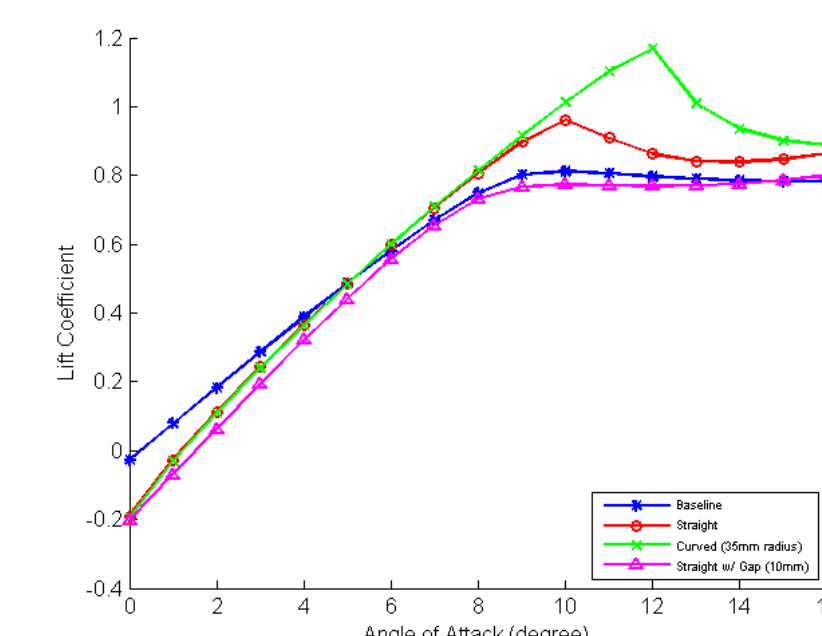


Figure 5: 2D Lift vs. Angle of Attack

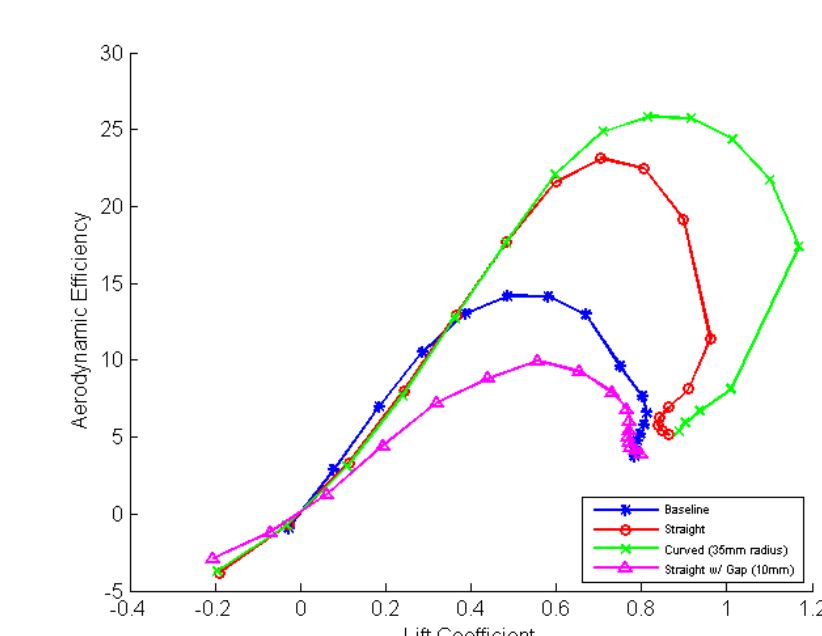


Figure 6: 2D Aerodynamic Efficiency vs. Lift

Results of 2D comparison study

- General Comparison: addition of a flap improved aerodynamic efficiency relative to the baseline case. Curvature improved performance over the straight geometry. Adding a gap degraded performance
- Curvature Study: low to moderate curvature improved performance over straight geometry. Excessive curvature caused flow separation and decreased aerodynamic efficiency
- Selection: Based on the 2D analysis, a curved flap cross section was chosen with a 40 mm radius of curvature and a length equal to 8 percent of the reference chord.

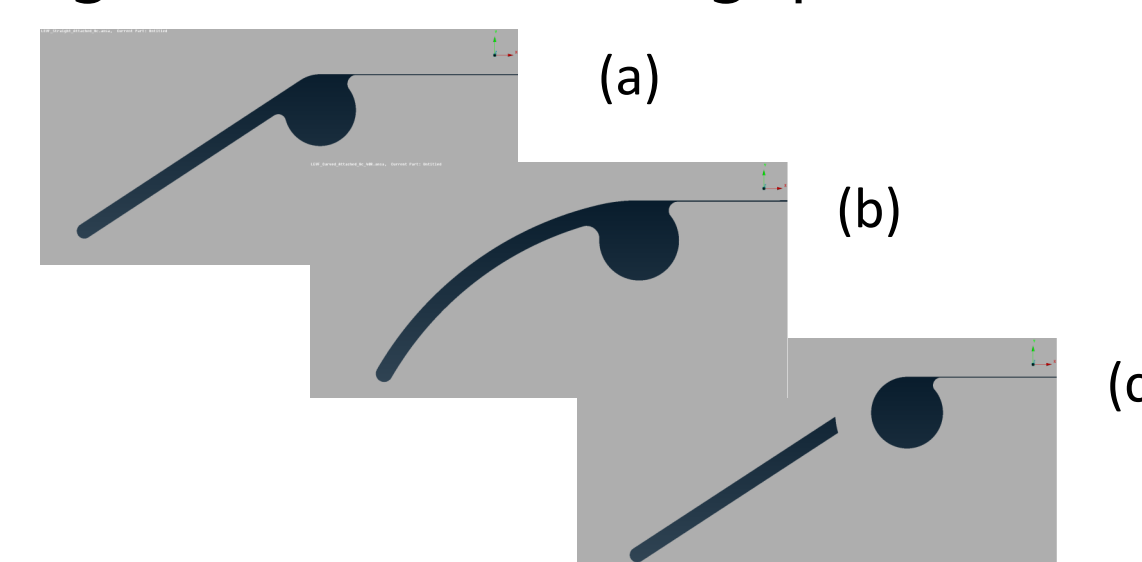


Figure 4: Vortex Flap Cross Sections; (a) Straight and Attached, (b) Curved, (c) Gap

3 Dimensional Analysis

In order to determine the viability of using LEVF devices to improve low speed delta wing aerodynamic efficiency, CFD analysis was performed on several three dimensional wing-vortex flap combinations that incorporated the cross sectional geometry detailed above. Wing sweeps of 30 and 60 degrees were considered in the study as well as an examination of the three dimensional flow effects caused by including a gap in the flap geometry.



Figure 7: Reference Configuration

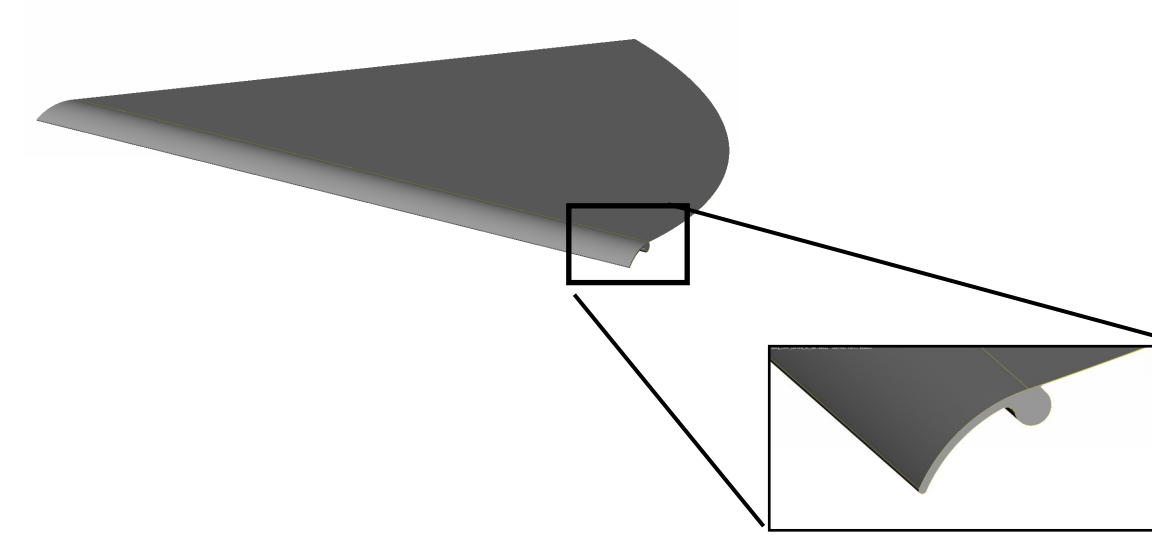


Figure 8: Attached Vortex Flap

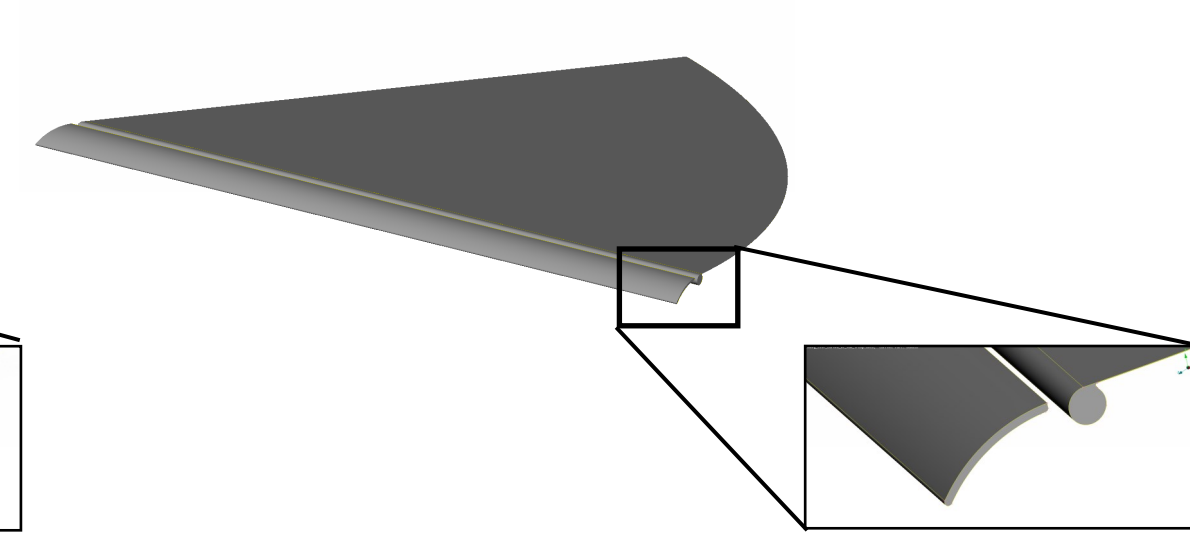


Figure 9: Vortex Flap with a Gap

Results of 3D Analysis

- Baseline Validation: reference configuration lift curve slope was 0.05 / degree in accordance with slender delta wing theory
- Aerodynamic Efficiency: the attached flap only slightly improved aerodynamic efficiency of the 30 degree wing while the 60 degree wing improved by 10 percent.
- Stall: flaps of both types generally increased the maximum lift coefficient and delayed stall.
- Moment: flaps tended to shift the aerodynamic center forward of the quarter chord location

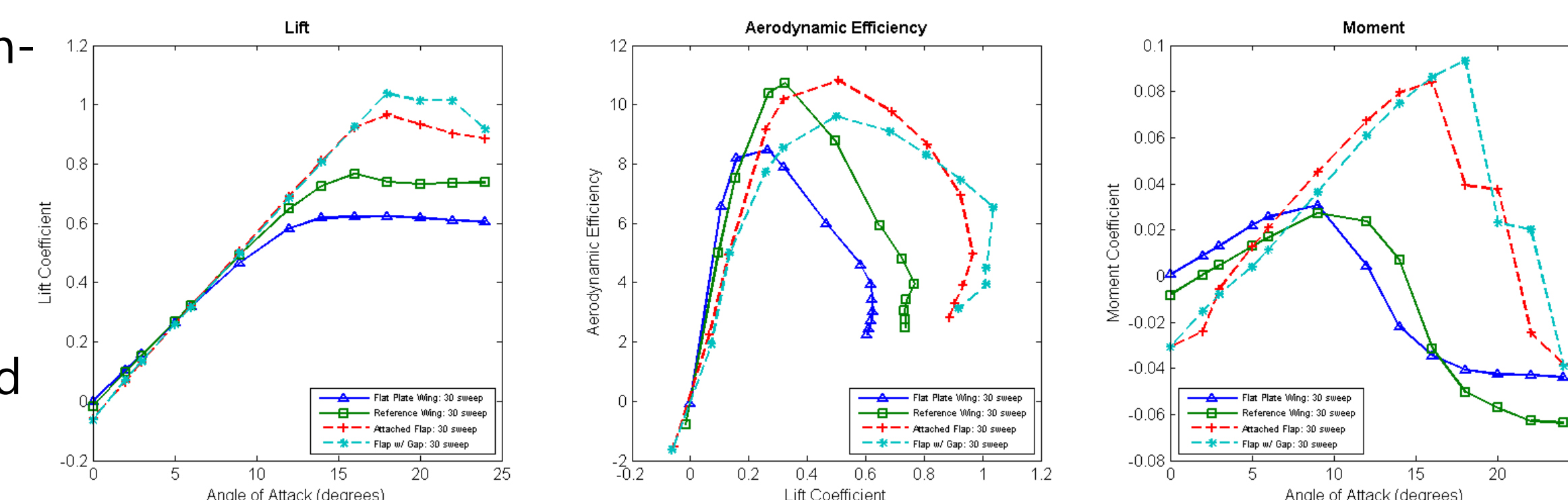


Figure 10: 30 Degree Delta Wing

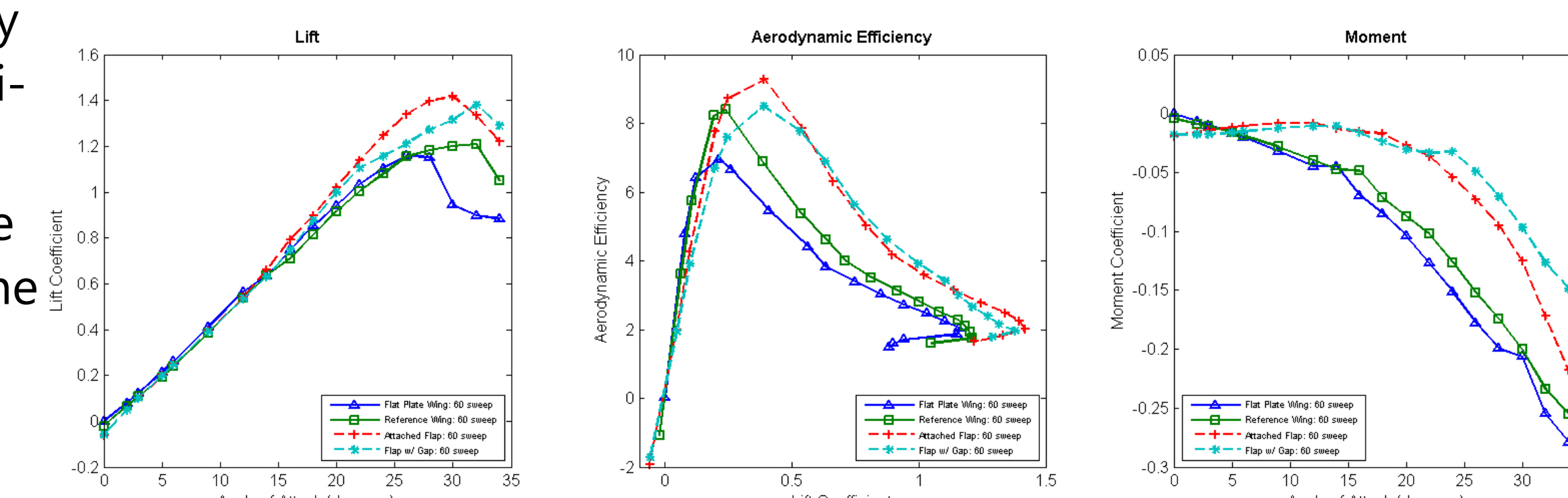


Figure 11: 60 Degree Delta Wing Data

CFD Post Processing

Geometry Comparison

Contrary to what was expected, CFD results showed that the attached vortex flap possessed a clear advantage in aerodynamic efficiency over the geometry with a gap. Post processing provided a clear illustration of the flow physics responsible for this phenomena. As can be seen in Figure 12, the force vectors are distinctly tilted forward providing an extra component of thrust whereas they are completely normal to the wing surface in Figure 13. The gap allows additional energy to be added to the flow and keeps the point of minimum pressure from moving forward onto the angled flap surface.

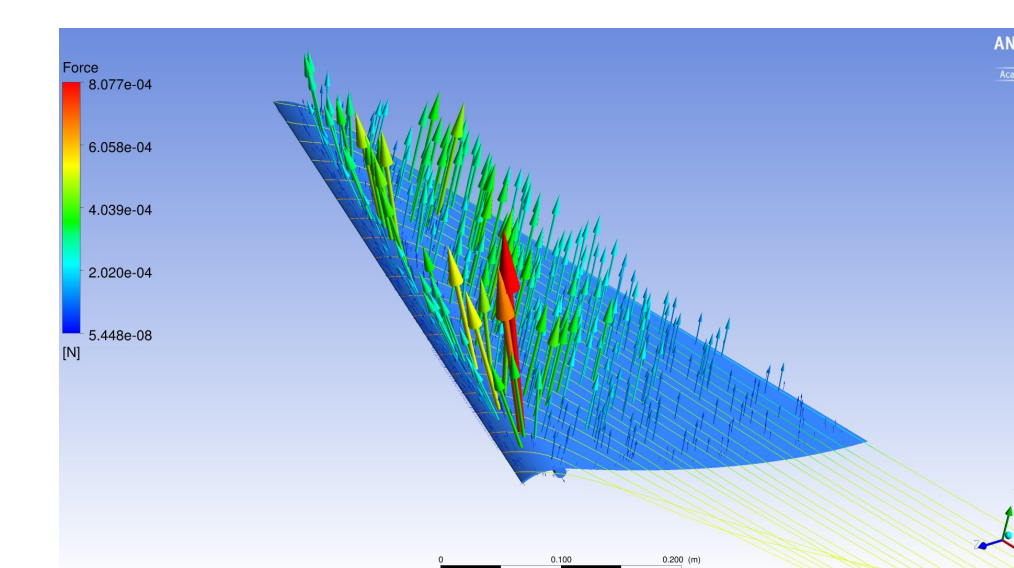


Figure 12: Attached vortex flap

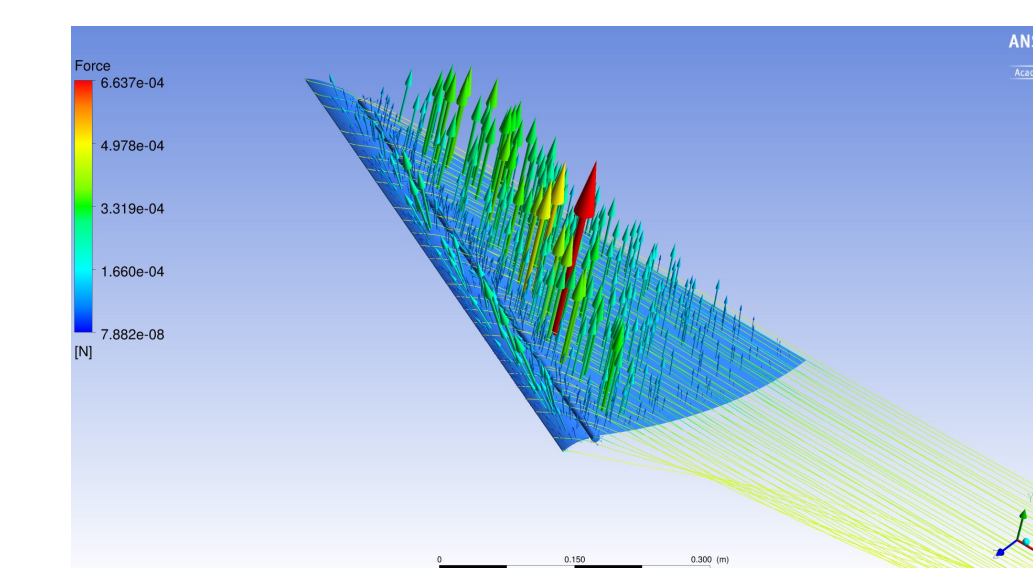


Figure 13: Vortex flap with a gap

Final Design

Based on the CFD Results, the attached vortex flap with 8 percent chord length and a 40 mm radius of curvature was chosen as the final design.

- It achieved the maximum overall aerodynamic efficiency for both 30 and 60 degree wing sweeps
- It generally provided better aerodynamic efficiency at higher lift coefficients and exhibited gentler stall behavior than the flap with a gap

Flap Deflection Study

Once the final geometry was selected, 4 additional flap deflection angles were tested over a full range of inlet boundary conditions.

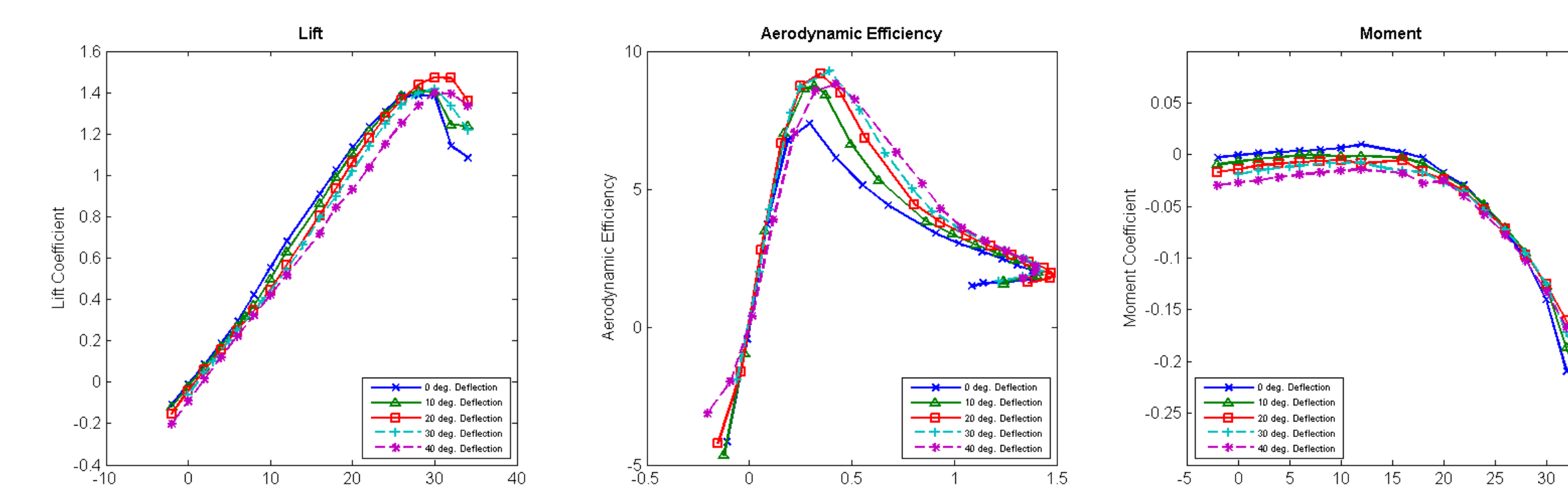


Figure 14: Vortex flap Deflection Study for the 60 degree wing

Conclusions and Future Work

- Curved, attached flaps marginally improved maximum aerodynamic efficiency but helped maintain significantly better efficiency at higher lift coefficients
- Leading edge flaps show potential as a means of providing positive longitudinal stability
- Future work would include flap geometry optimization, multi-element deflection analysis, and wind tunnel verification

References

- [1] Anderson, John D. Fundamentals of Aerodynamics. Boston: McGraw-Hill, 2001.
- [2] Kuethe, Arnold M., and Chuen-Yen Chow. Foundations of Aerodynamics: Bases of Aerodynamic Design. New York: Wiley, 1986.
- [3] Whitfield, C.A., Warchol, M. "Flight Performance Characteristics of Highly Flexible Wing Rogallo-type Aerodynamics with Applications to UAVs." AIAA Dayton-Cincinnati Aerospace Sciences Symposium, 1-March 2011.